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AIR FORCE FLIGHT DYNAMICS LABORATORY
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HYSTERESIS STUDIES OF 7075 MATERIAL TEST PERFORMED BY SCHIJVE AND JACOBS

Prepared by

Capt. D. Hayes

Air Force Flight Dynamics Laboratory

Lt. B. Duncan

Aeronautical Systems Division

Technical Memorandum FBR-74-54

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FOREWORD

At the request of Messrs. W. J. Crichlow ASD/ENF and R. Bader, AFFDL/FBR an analytical program was performed to evaluate the capabilities of the Hysteresis Fatigue Analysis to predict the results of a series of tests performed by J. Schijve and F. A. Jacobs.

The Hysteresis Fatigue Program was developed by E. K. Walker, Lockheed California Company and Captain D. Hayes, AFFDL/FBR.

This report covers work accomplished from 1 February 1974 to 1 March 1974 under Project 1467, Task 146703, Fatigue and Fracture Design and Analysis Methods.

The authors wish to thank Mr J. M. Potter AFFDL/FBR for providing data from his sequence Accountable Fatigue Program.

The Manuscript was released by the author in May 1974. This Technical Memorandum has been reviewed and is approved.

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I. INTRODUCTION

The Hysteresis fatigue Analysis (HFA) method, Reference 1, uses a cyclic stress-strain curve in conjunction with a Neuber analyses to describe a notch stress-strain history. The notch stresses are then used in a damage theory which employs an equivalent stress. The HFA does not incorporate a model of cyclic stress relaxation. The purpose of the current effort is to ascertain if, without such a model, the HFA is capable of predicting a series of test results for 7075-T6 aluminum performed by J. Schijve and F. P. Jacobs and reported in Reference 2. This is accomplished by comparing the predictions from the HFA to test results. The HFA predictions are then compared to predictions of the same test lives using the Sequence Accountable Fatigue Program (SAF) developed by Potter and reported in Reference 3. Potter's program employes a decay function which relaxes residual stresses as a function of cycles.

To ascertain if the differences in the two fatigue life prediction methods could possibly be attributed to relaxation, a parametric study was made. This paper describes the results of that study.

II. LOAD SPECTRA

A series of nine loads spectra from Reference 2 were analyzed. The stresses for these spectra are depicted graphically in Figure 9. The test series numbers used in Reference 2 are used here for convenience to identify each spectra.

III. S-N DATA

As seen in Figure 9, each test series has the same four low amplitude stress levels. These levels produce elastic notch stresses. Schijve and Jacobs performed a set of constant amplitude tests at each of these four levels.

The Potter method was used to analyze test series 10 using MIL-HDBK-5 constant amplitude S-N data and selecting an effective $K_t = 4.125$ as the most representative. Test series 10 had no overloads. The authors adopted the same effective K_t so that direct comparisons between the HFA and SAF methods could be made.

The S-N Data used for the HFA method is in terms of an effective stress versus N. where the effective stress is of the form:

$$\bar{\sigma} = \sigma_{max} (1 - R)^m \tag{1}$$

In equation (1) σ_{max} is the maximum stress at the concentration. For the four lowest levels mentioned above this is simply 4.125 S_{max}.

Thus four points for the $\bar{\sigma}$ vs N curve were established from Schijve's constant amplitude tests assuming the $\bar{K}_t$ of the coupons was 4.125.

Since Schijve did not develop any constant amplitude data for these coupons above 10^6 cycles or below 10^5, the high and low ranges had to be approximated. The high end was established from 7075-T6 S-N data taken from Walker (Ref 5). Since the four points from Schijve's constant amplitude data were a straight line on a log x log scale this line was extended to give the low stress $\bar{\sigma}$ vs N portion of the curve. Thus the authors assumed that 7075-T6 has no endurance limit. The complete $\bar{\sigma}$ vs N data is presented in Figure 1.

IV. THE LIFE PREDICTIONS

The HFA method was used to calculate the notch stress-strain hysteresis loops for the test sequences (Figures 2-8). In each case the block loading is shown both before and after the overload. Stresses from Figures 2-8 were used in Equation 1 to find the equivalent stresses $\bar{\sigma}$. If the stress ratio, R, was very negative (ie., $R \leq -\frac{1}{2\alpha}$ where α is Poisson's ratio) the equivalent stress equation used was the following:

$$\bar{\sigma} = \frac{2}{3} \sigma_{min} (1 - R)^m \tag{2}$$

Equation 2 would account for damage due to Poisson tensions. At this point a Miner's linear summation was used for damage where,

$$\text{Damage,} \quad D = \sum \frac{n}{N} \tag{3}$$

The equivalent stress from Equation 1 or 2 was used in Figure 1 to find the denominator N in Equation 3. Life was then calculated from damage as follows:

$$\text{Life (Blocks)} = \frac{1 - D\ (\text{Block 1})}{D\ (\text{Block 2})} + 1 \tag{3a}$$

Where D (Block 1) refers to the summation of damage for the first time through the loading sequence and D (Block 2) is the summation of damage for the second and subsequent blocks of loading. These will generally be different due to the residual stresses. Since no relaxation is employed only two repetitions of the loading block need to be analyzed. The results of these life predictions are shown in Figure 9 along with the results for the SAF method.

In test series 10, 8, and 7 the mean stress of the block loading was not significantly affected by the overload (see Figures 2, 5, and 8). Thus the results of these tests were easily predicted by both the HFA and the SAF methods. In test sequence 8 the residual stress produced by the high positive overload was immediately removed by the negative unloading (See Figure 5).

For the remainder of the test sequences there were residual stresses present following the overloads.

Discussion of Relaxation

The tests performed by Schijve contained 80,000 cycles per block. The loads, with the exception of a once per block overload, produced elastic notch stresses. Potter's method incorporates a residual stress relaxation function of the form

$$\sigma_{res} = (\sigma_{ores} - \sigma_{EQres}) \exp \left(\frac{N}{N_{ePi}} \ln (0.1)\right) \tag{4}$$

where σ_{res} is the instaneous residual stress

σ_{ores} is the residual stress from the previous loading

σ_{EQres} is the equilibrium component of residual stress

N_{ePi} is dependent upon the applied stress on a relaxation constant

$$N_{ePi} = f\ (C,\ S\ \text{applied}) \tag{5}$$

N = Number of cycles of an applied stress.

According to Potter (Ref 3) the relaxation constant should be a constant for a given material.

The relaxation model of Equation 4 relaxes the residual stresses, that is the difference between the mean stress of the loading before and after the plastic overload (See Fig. 2-8). In the four tests (5, 6, 9, and 17) where the overload established a significant residual stress, this function will cause the residual stress to decrease and become less negative, thus increasing the amount of damage attributed to the subsequent loads.

If the same function was used in the HFA this increase in damage would only improve the results for the test series 5, 6b, and 17 which were predicted to last longer than the test mean life. Of these three tests only test 5 was predicted outside of the scatter of the test data (See Fig. 9). In test series 6, 6a, and 9 a relaxation function such as Equation 4 would cause an increase in damage and cause the HFA life predictions for these tests to be even more conservative. It is therefore apparent that the differences in the predicted lines between the HFA and SAF programs can be attributed to factors other than residual stress relaxation. This is because the HFA without relaxation of residual stresses was able to predict test lives within the scatter of the tests or below the test mean for all the test sequences except test 5. A parametric study was made to assess these differences.

Comparative Study

As indicated above there are other differences in the HFA and SAF programs than relaxation. The Stress Analysis, SN data and damage theory are also different.

One very basic difference between the two programs is the Stress-strain history description. In this study the HFA used a stress-strain curve for 7075-T6 AL from Morrow (Ref 4), while the SAF assumes an elastic - perfectly plastic stress-strain behavior. The difference between these two assumptions for 7075-T6 can be seen in Figure 11. The Morrow data was scaled to the Schijve data by yield stress to model the particular sheets of aluminum used in the tests. For all the tests except 8 and 9 the monotonic curve was used. It was felt by the authors that strain hardening probably would not occur since the plastic strains were few and not complete reversals. For tests 8 and 9 the cyclic curve was used since the overloads in these tests were reversed. In test 8 the choice was of little significance since the residual stresses introduced were removed by unloading. However, due to the short life of the test 9 specimens a hardening law should have been employed. Morrow indicates 7075-T6 completely hardens in approximately 10 strain reversals. This would be about half the life of the test 9 coupons so the accuracy of using the cyclic stress-strain curve for test 9 is at least questionable.

After a high plastic overload both programs unload elastically. Thus the HFA being at a higher stress state would cycle about a higher mean stress than would the SAF program. Thus the SAF without relaxation would tend to be less conservative. The higher the overload (more plasticity) the greater the differences in stress levels between the two analysis methods. The test life predictions using the SAF with C = ∞ (no relaxation) is shown in Figure 12. It can be seen that without relaxation the SAF is very unconservative. To ascertain if this unconservatism was entirely due to the lack of relaxation the notch stresses calculated from the SAF method were used with the damage analyses of the HFA. These results are also presented in Figure 12. It can be seen that for the tests with significant residual stresses (ie, tests 5, 6, 9, 17) the SAF is very unconservative without relaxation. When the Schijve S-N is used in the manner described for the HFA in conjunction with the stresses from the SAF the results of the SAF program are still unconservative. Also, the larger the overload the more unconservative the analysis. A possible cause for this may be because the perfectly plastic distortion law gives larger residual stresses than would be obtained with a stress-strain curve. A table of life predictions for the parametric study is shown in Table 1.

CONCLUSIONS

For the series of tests reported, and the analyses conducted during this study the following can be concluded:

1. The Hysteresis fatigue analysis predicted the test results for all the tests where the stresses were elastic or nearly elastic (tests 10, 8, 7).

2. A stress-strain curve to model material behavior is more conservative than a perfectly plastic model.

3. A relaxation function which relaxes residual stress would not improve the accuracy of the HFA.

4. TheSchijve data was not conclusive in determing if the effects experienced were due to cyclic relaxation or some other phenomena. The data had large amounts of scatter for some series and the coupons were complex.

RECOMMENDATIONS

1. An experimental program is needed to determine the cyclic behavior of a material after a preload.

2. An experimental program is needed to establish a precise local stress-strain history under cyclic loading. Such a model would be physical in nature and would include hardening (or softening), relaxation, temperature effects and time dependent creep.

3. A damage theory is needed which has a physical basis. Such a model would probably be based on energy concepts.

4. A complete damage analysis is needed which can account for physical behavior and eliminates such nebulous terms as "crack initiation" and "fatigue life". Such a model would include crack growth and be statistical in nature.

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4. T. Endo and J. Dean Morrow, "Cyclic Stress-Strain and Fatigue Behavior of Representative Aircraft Materials," paper presented at the 70th Annual Meeting ASTM. Boston. Mass. June 1967.

5. Walker, K. "The Effect of Stress Ratio During Crack Propagation and Fatigue for 2024-T3 and 7075-T6 Aluminum," ASTM STP 462, American Society for Testing and Materials, 1970, page 1-14.

6. Rotvel, R., "On Residual Stresses During Random Load Fatigue," Technical University of Denmark, Lyngley, Denmark.

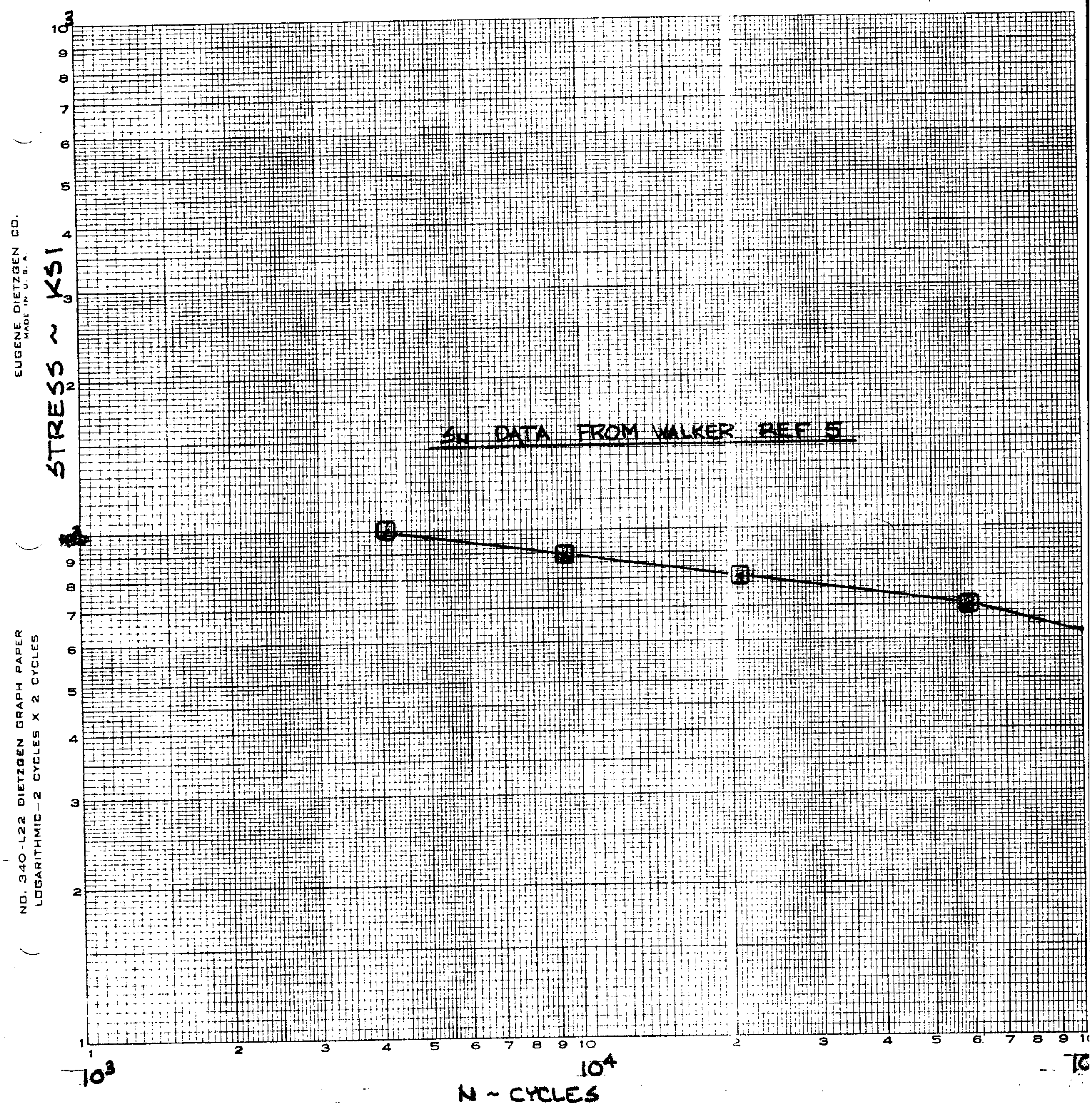

STRESS ~ KSI
SN DATA FROM WALKER REF 5
N ~ CYCLES
10³
10⁴
EUGENE DIETZGEN CO.
MADE IN U.S.A.
NO. 340-L22 DIETZGEN GRAPH PAPER
LOGARITHMIC-2 CYCLES X 2 CYCLES

FIG 1. SN DATA

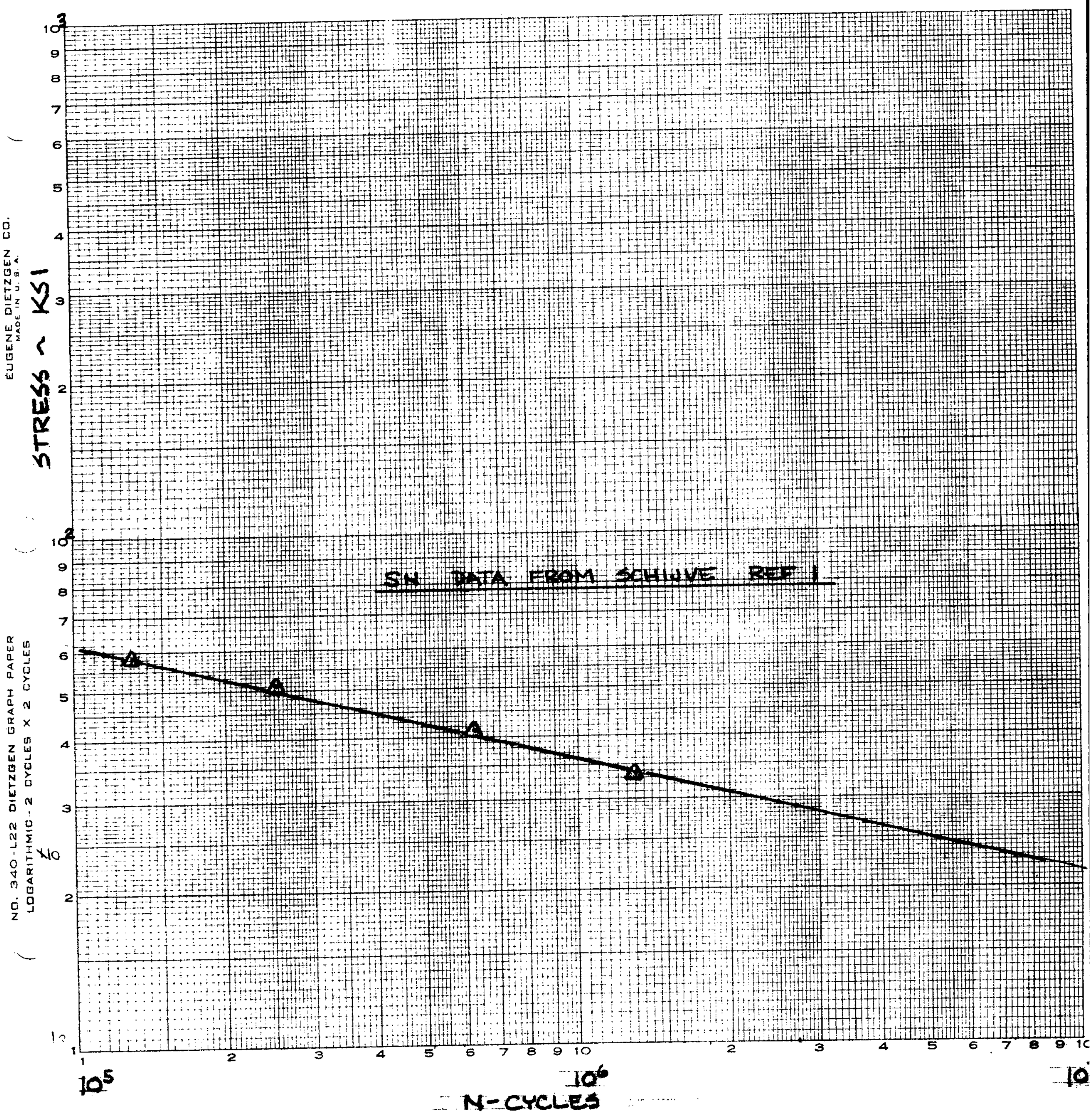


FIG 1 (CONT.) SN DATA

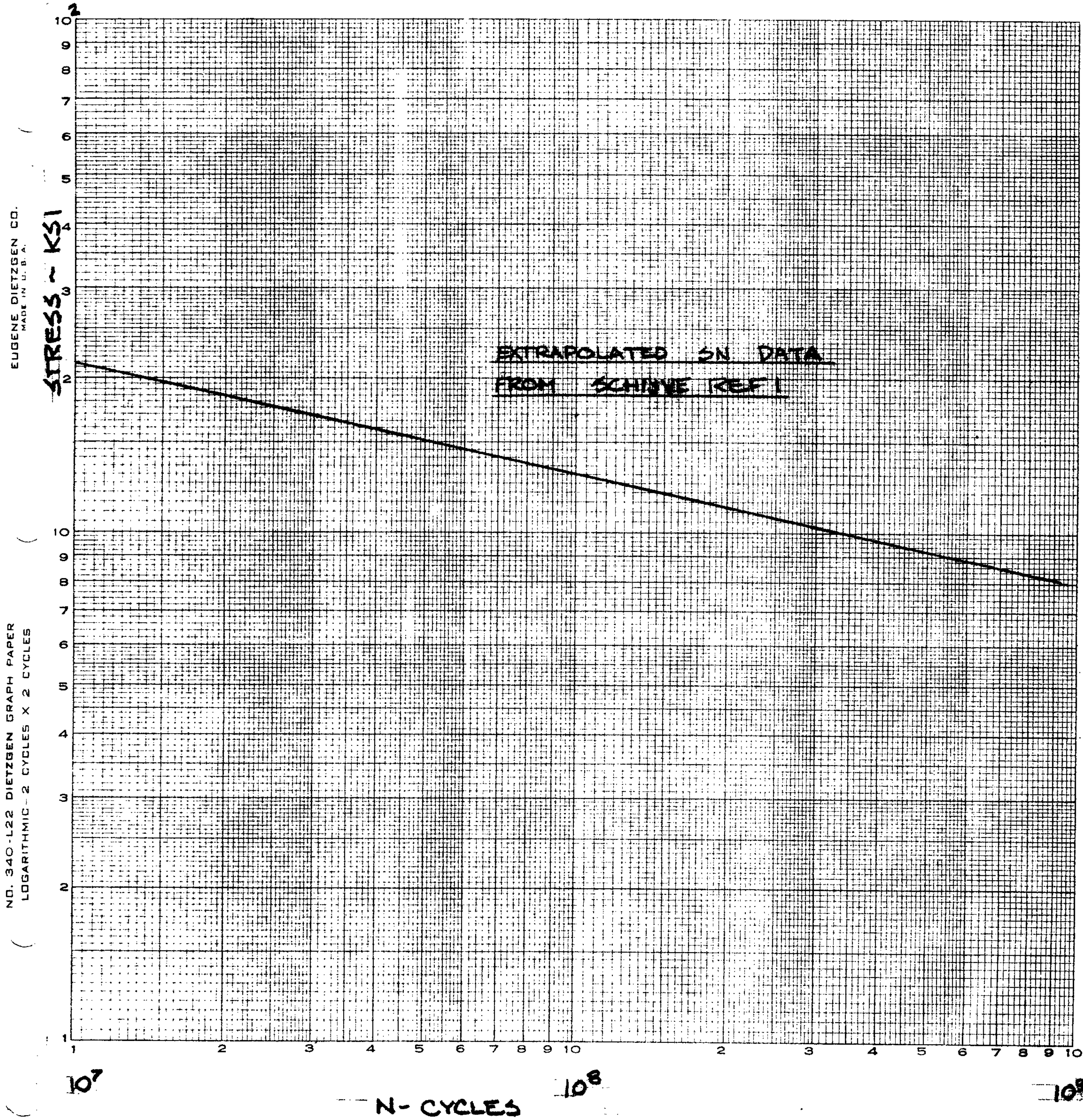


FIG 1 (CONT) SN DATA

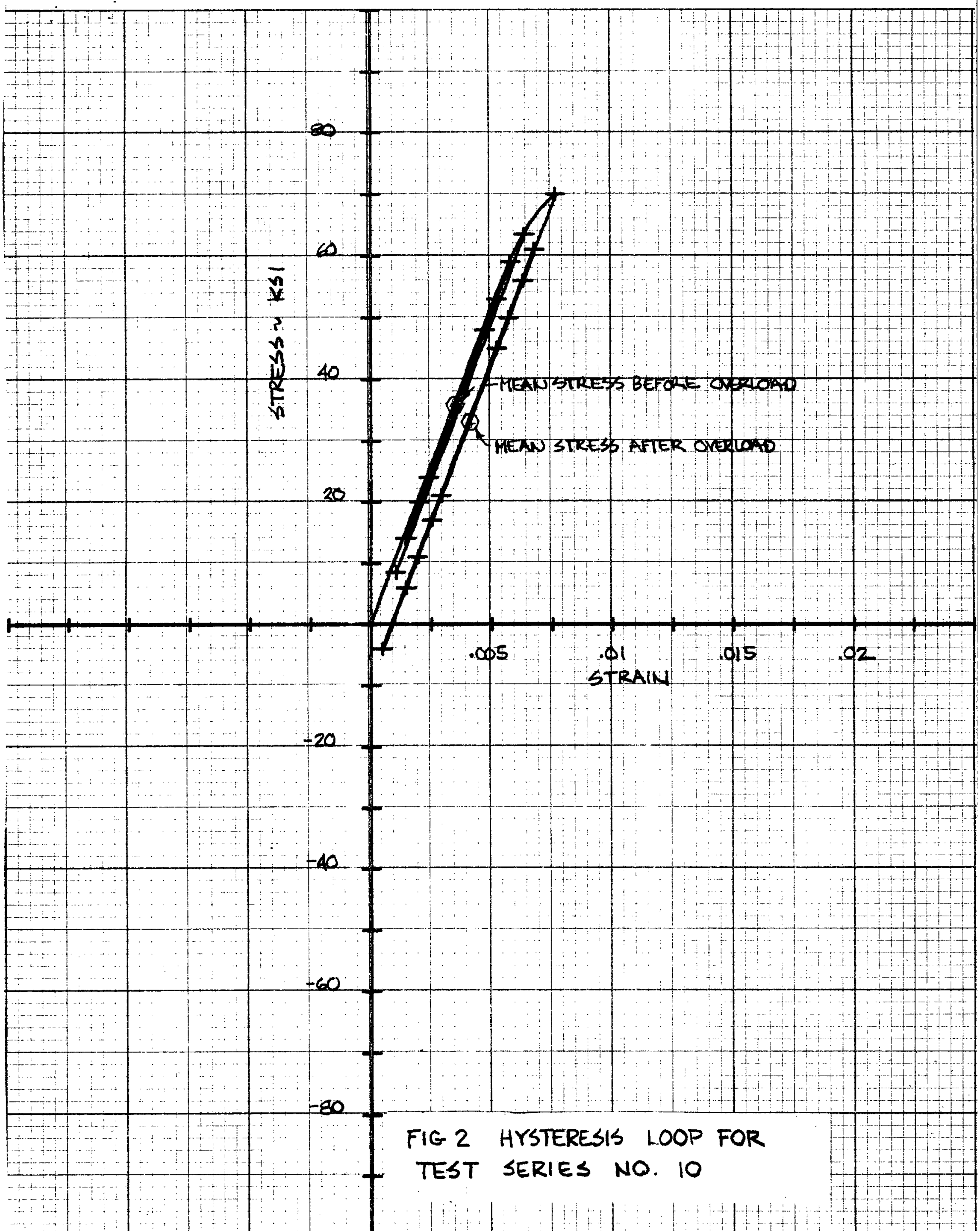


FIG 2 HYSTERESIS LOOP FOR TEST SERIES NO. 10

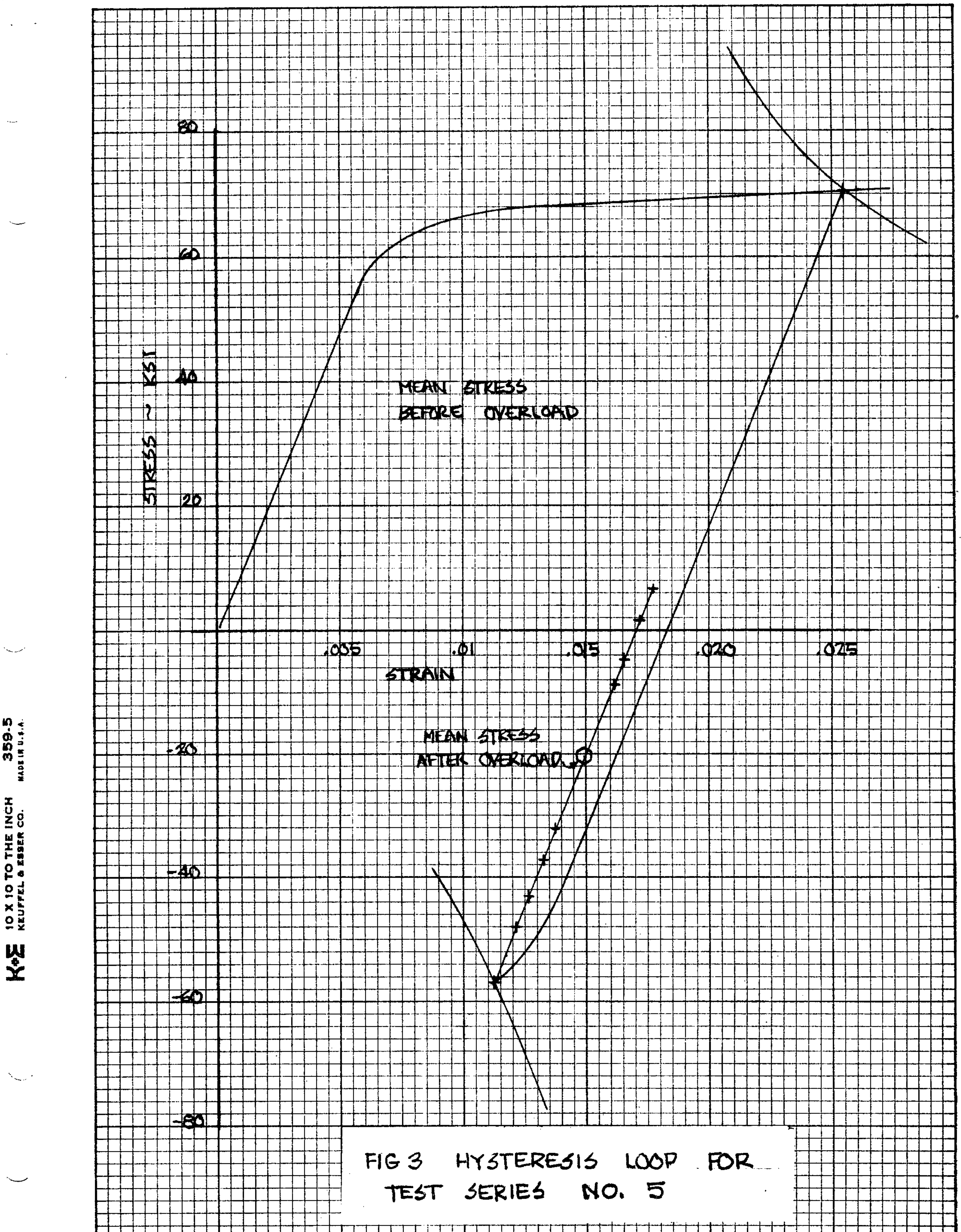


FIG 3 HYSTERESIS LOOP FOR
TEST SERIES NO. 5

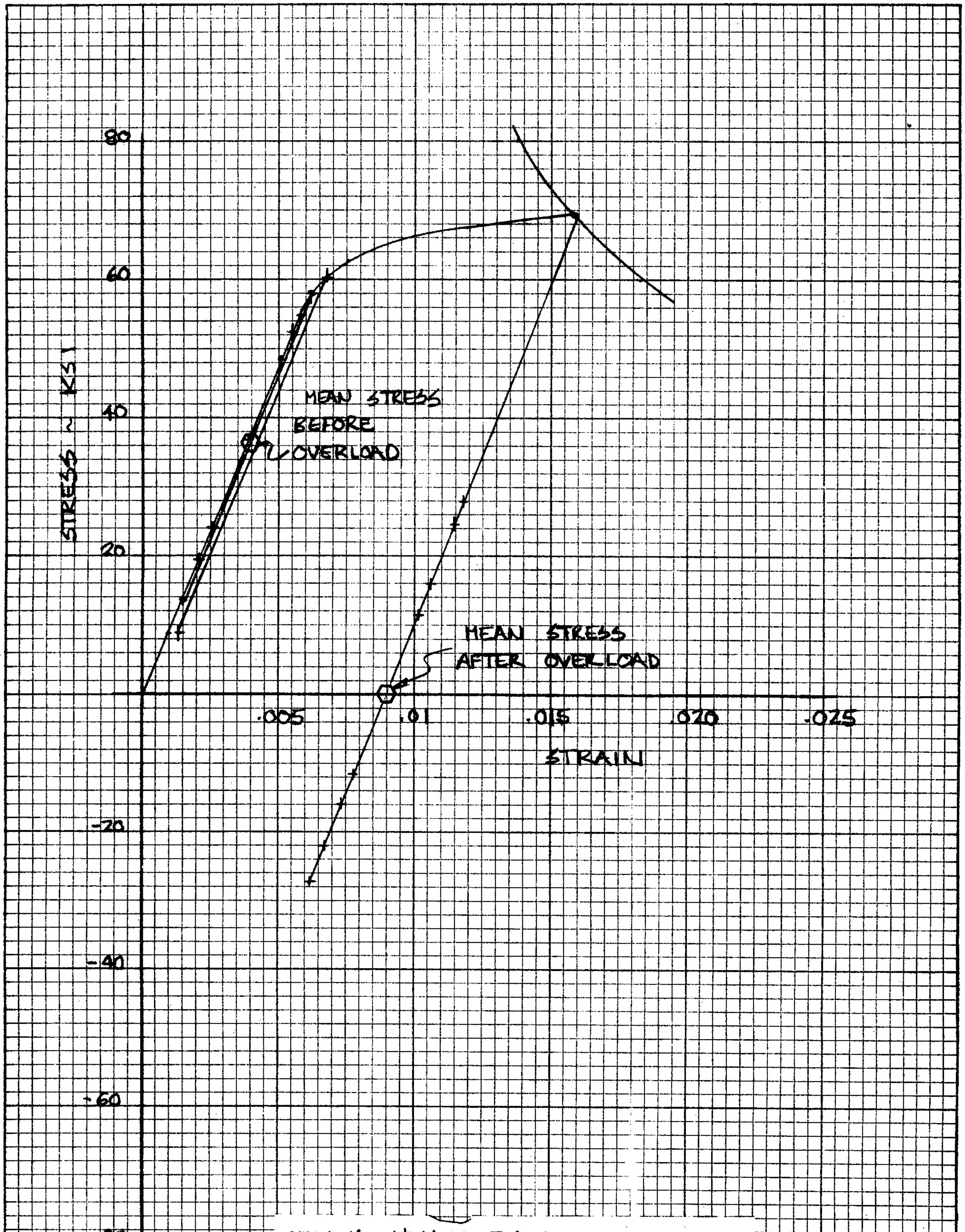


FIG 4 HYSTERESIS LOOP FOR TEST SERIES NO. 6

10 X 10 TO THE INCH 359-5 KEUFFEL & ESSER CO. MADE IN U.S.A.

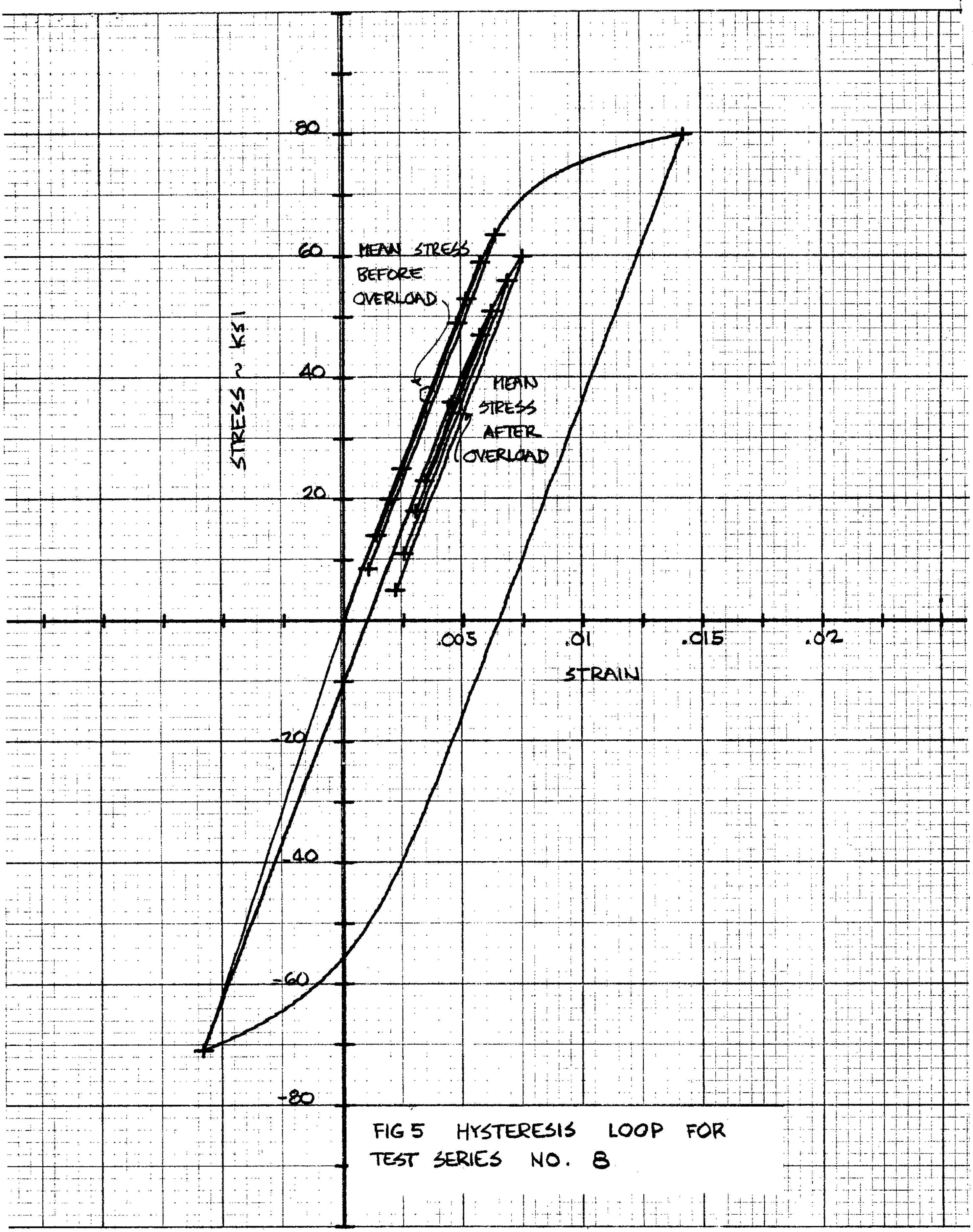


FIG 5 HYSTERESIS LOOP FOR TEST SERIES NO. 8

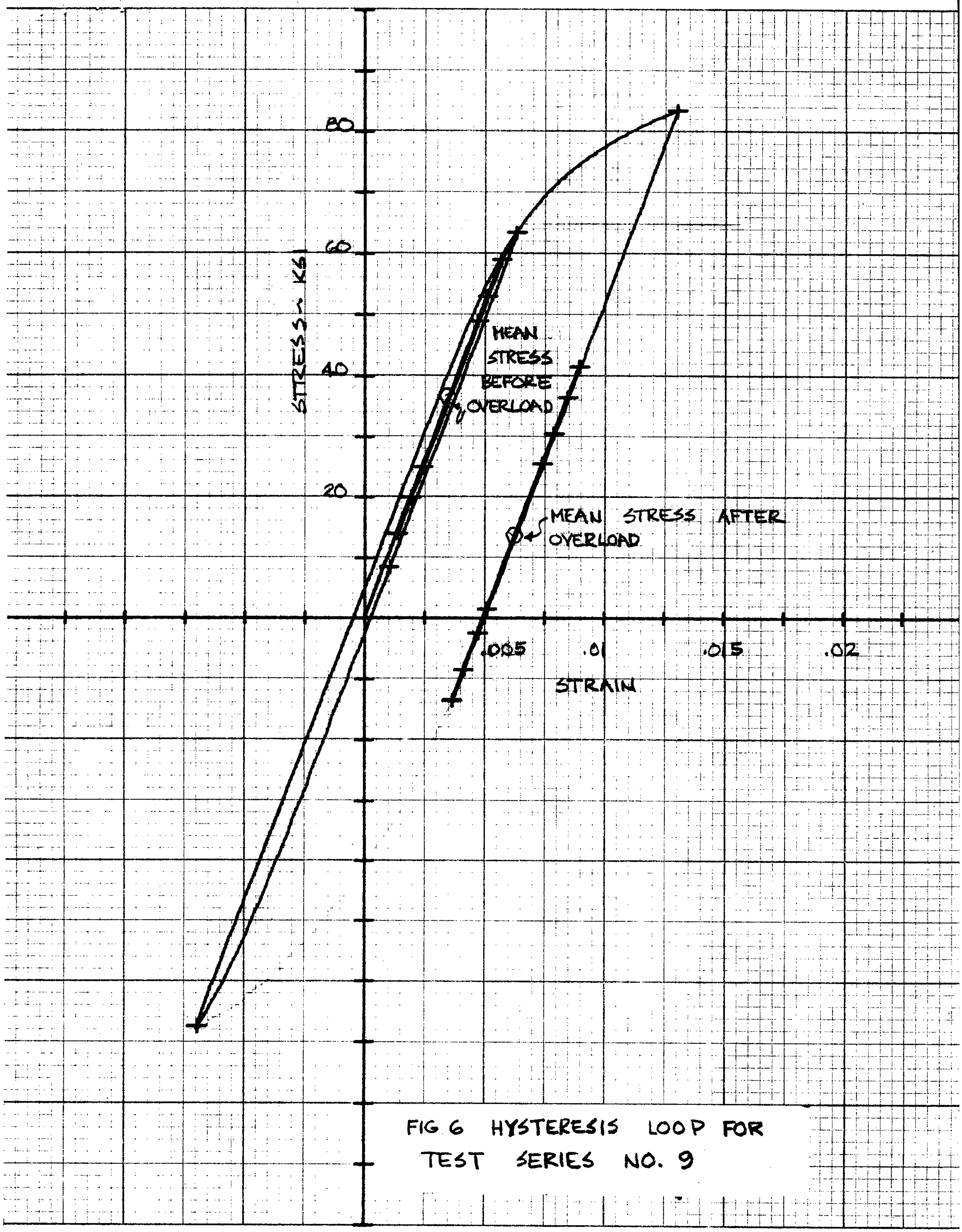


FIG 6 HYSTERESIS LOOP FOR TEST SERIES NO. 9

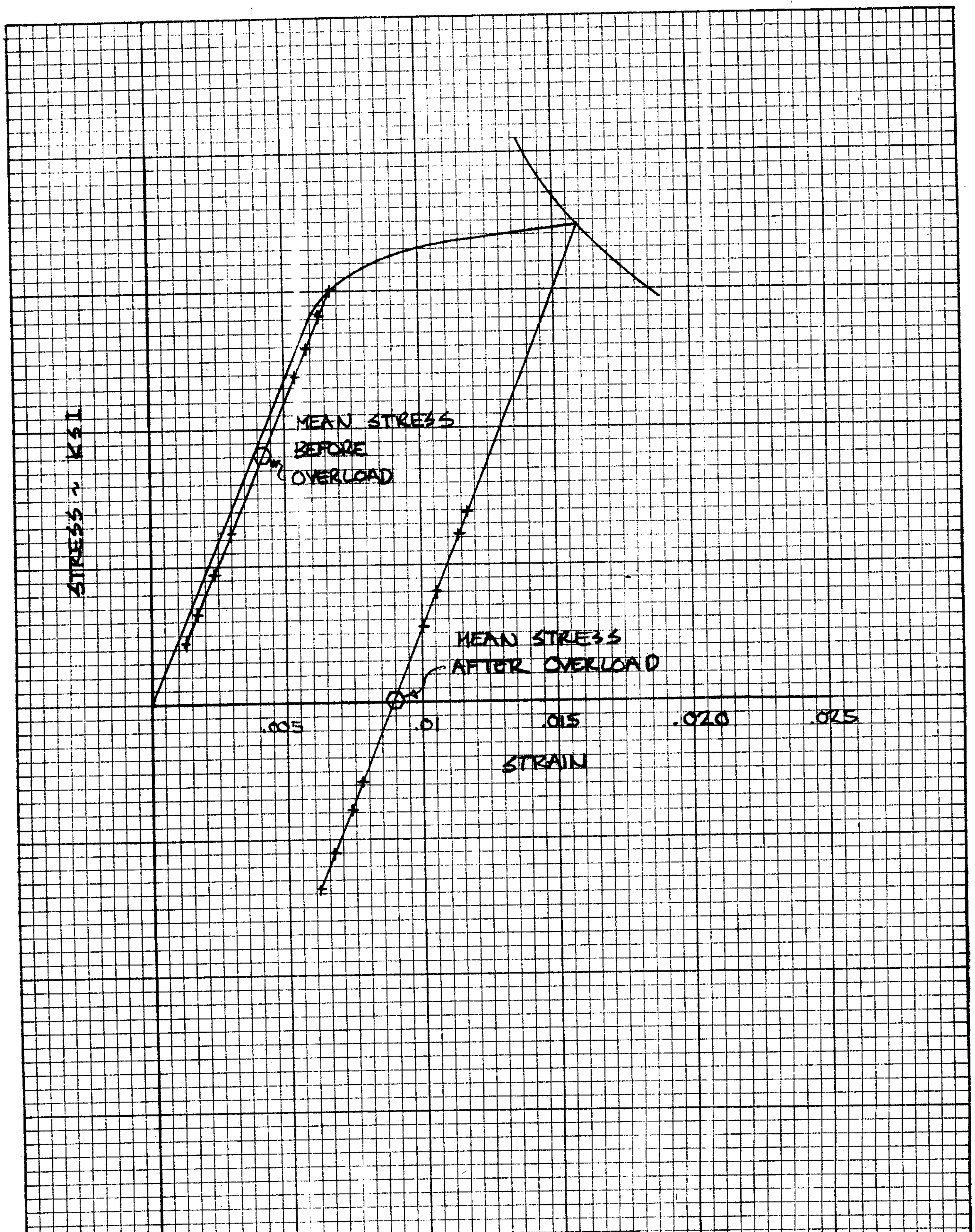


FIG 7 HYSTERESIS LOOP FOR TEST SERIES NO. 17

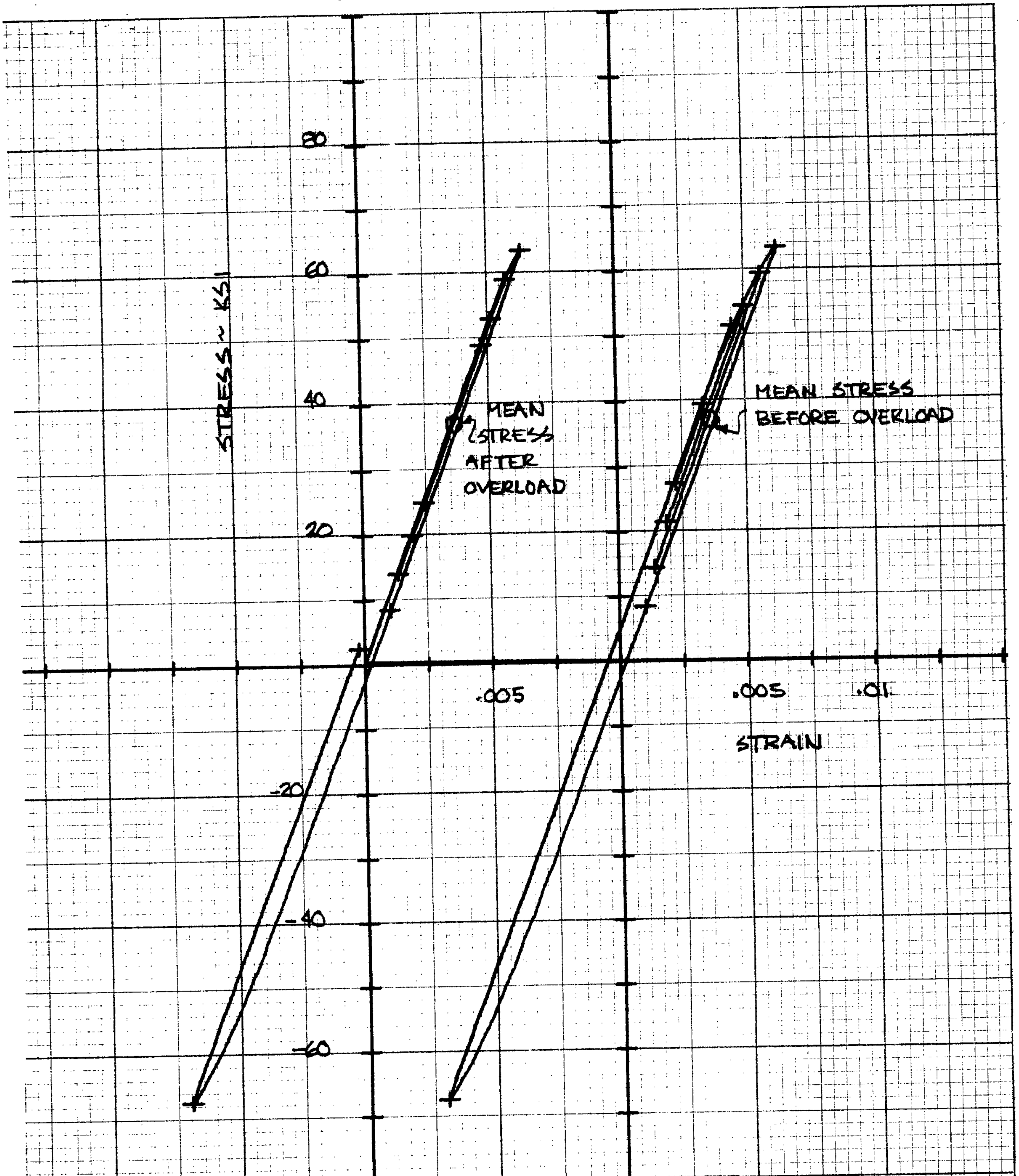
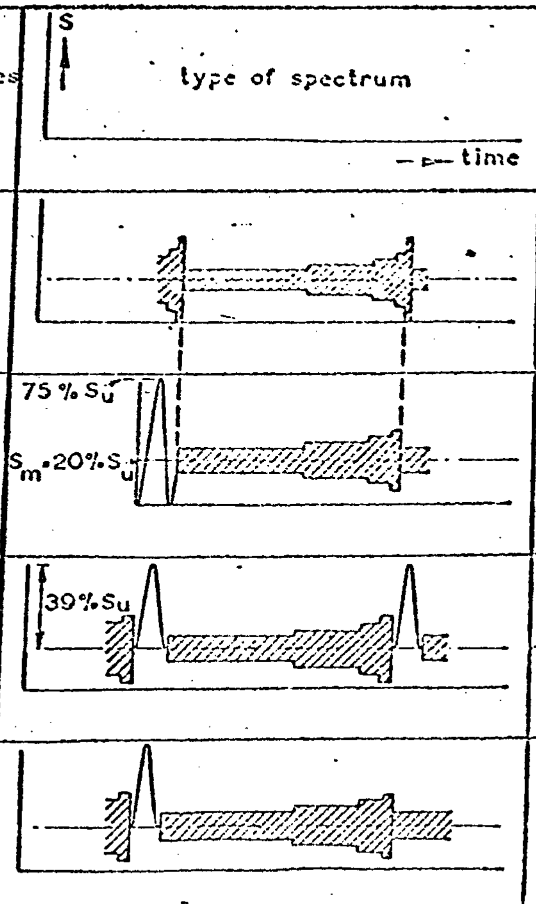


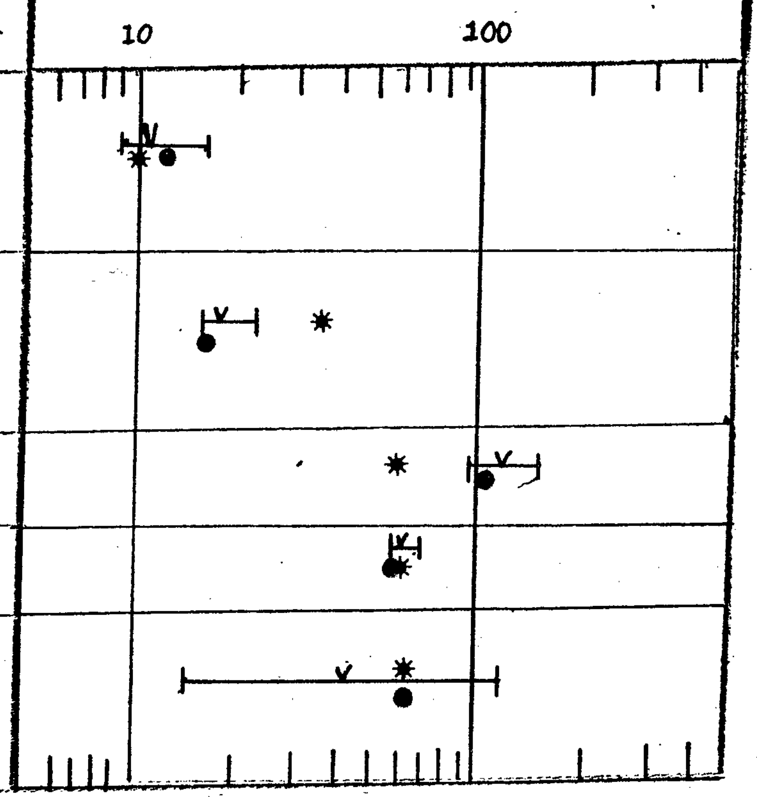
FIG 8 HYSTERESIS LOOP FOR TEST SERIES NO. 7

FIG 9 from SCHIJVE AND JACOBS, NLR 2070

7075 riveted panels

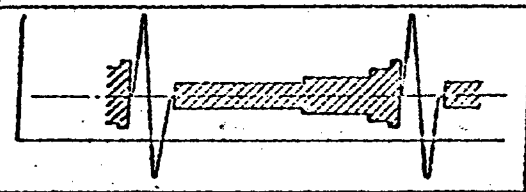
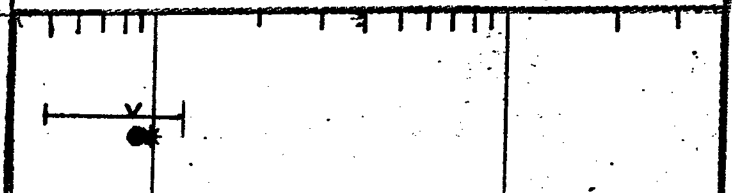
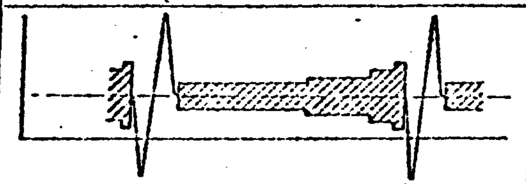
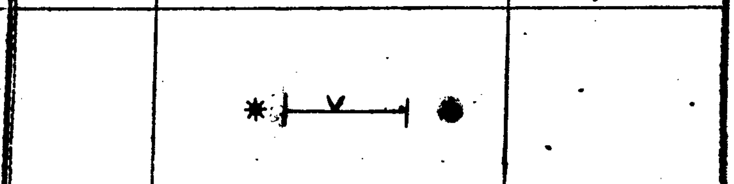
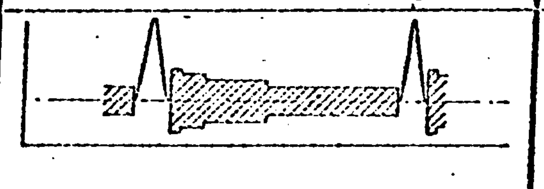
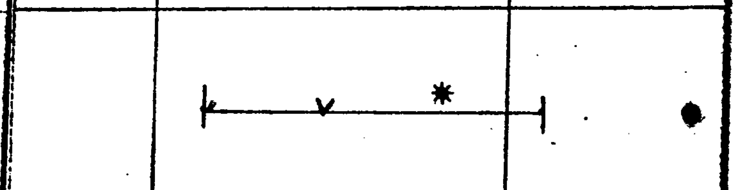
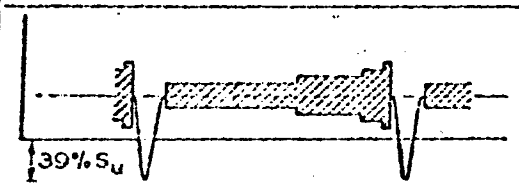
Test series	Type of spectrum	Similarity with other test series	Fatigue Life, Blocks
10		Taylor's gust spectrum	
5		One high pre-load, spectrum of series 10, highest S_a omitted	
6		Spectrum of series 5, one high positive load at the end of each period	
6a		Similar to series 6, however high loads omitted after $\Sigma \frac{n}{N} \sim 4.65$ (50th period)	
6b		Similar to series 6, however high loads at the end of odd numbered periods only	





V MEAN LIFE PREDICTIONS
SCATTER
HFA PREDICTIONS
SAFP PREDICTIONS

FIG 9 (CONT.) 7075 Riveted panels, continued

Test series	type of spectrum (S vs. time)	Similarity with other test series	Fatigue Life, Blocks (10, 100)
8		Similar to series 6, high positive loads now follows by high negative loads	
9		Similar to series 8, high loads in reversed order	
17		Similar to series 6, however, spectrum in reverse order	
7		Similar to series 6, however, high negative loads instead of high positive loads	

PREDICTED FATIGUE LIFE

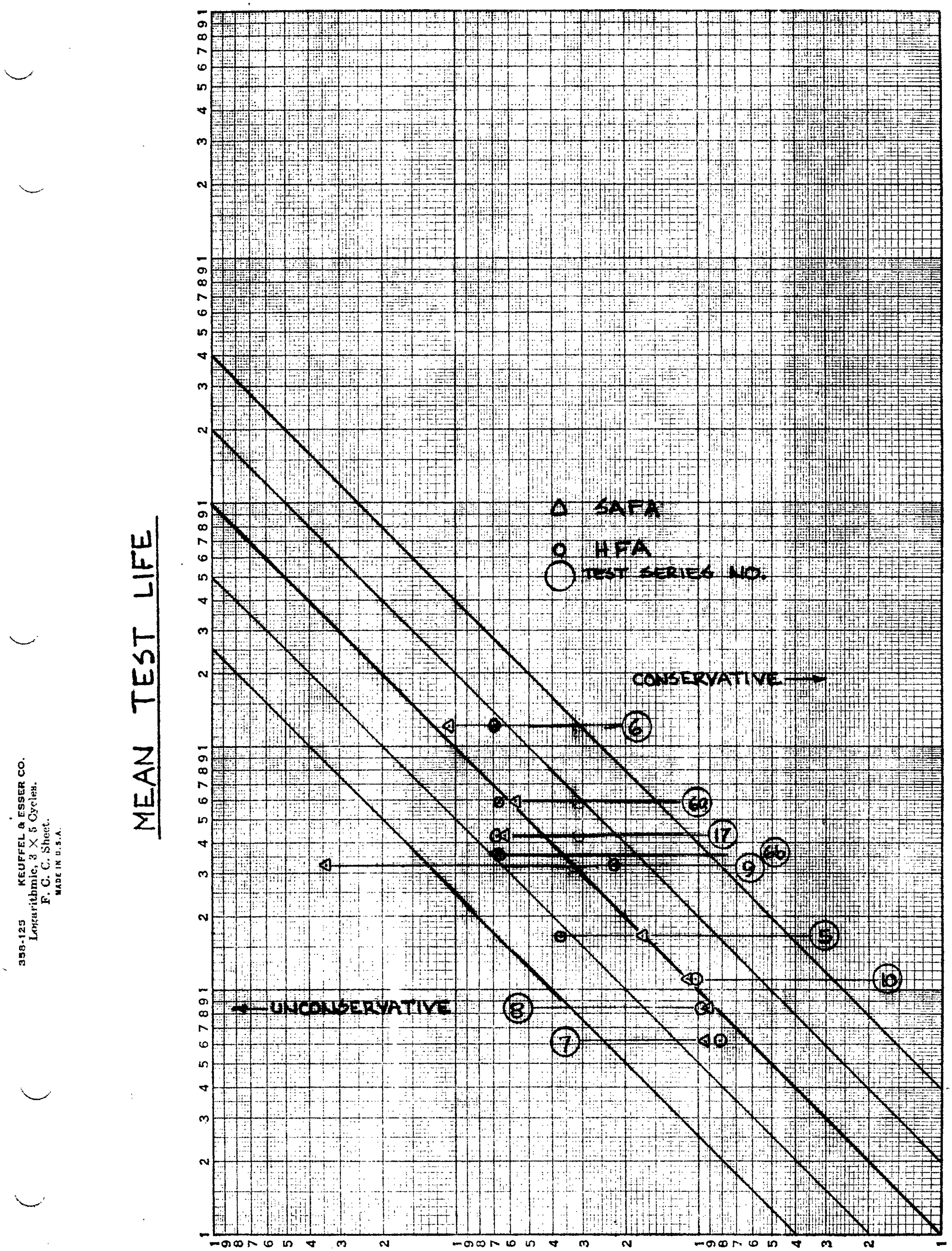


FIG 10 FATIGUE LIFE PREDICTIONS

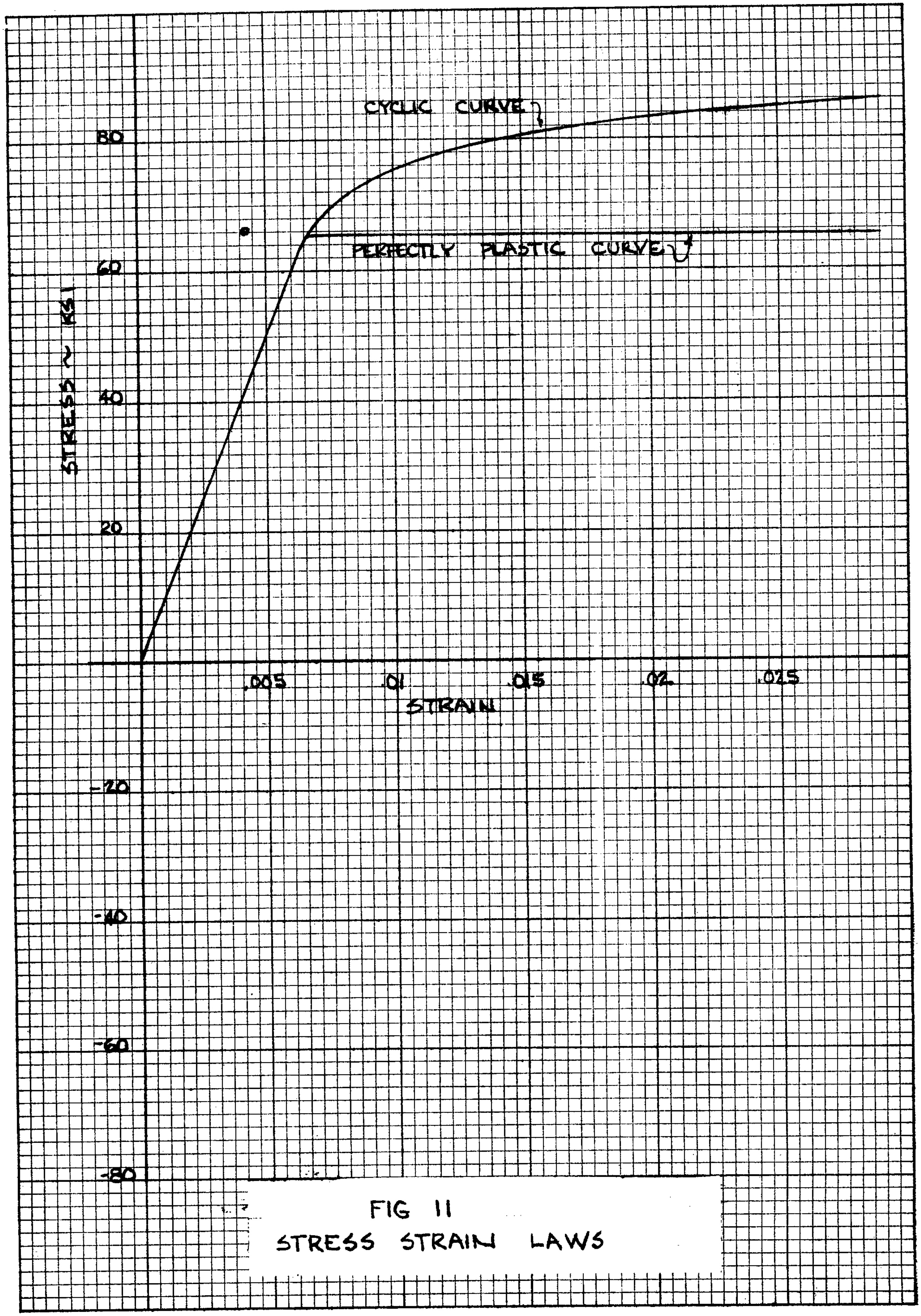


FIG 11
STRESS STRAIN LAWS

PREDICTED TEST LIFE

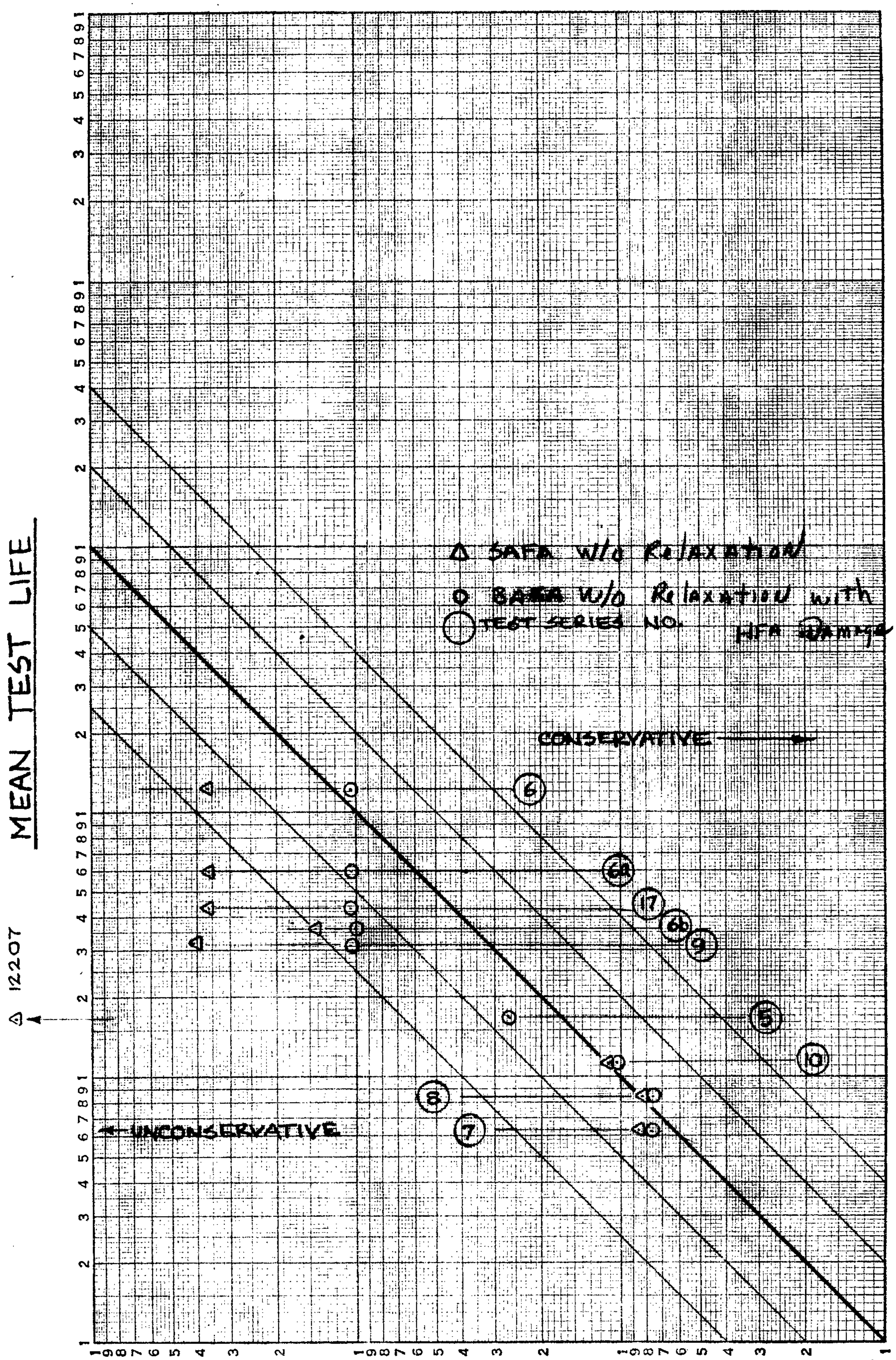


FIG 12 FATIGUE LIFE PREDICTIONS

TABLE 1. PARAMETRIC STUDY

1	2	3	4	5	6
TEST SERIES	SAF STRESSES MIL HbK SN NO RELAXATION	SAF STRESSES MIL HbK5 SN RELAXATION $C = 640 \times 10^6$	SAF STRESSES HFA Damage NO RELAXATION	HFA STRESSES HFA Damage NO RELAXATION	MEAN TEST LIFE
10	12.00	12.00	10.38	10.15	11.06
5	12207.	17.06	26.6	37.62	16.75
6	363.4	106.8	104.4	67.0	121.52
6a	363.4	57.05	104.4	67.0	59.62
6b	363.4	63.76	104.4	67.0	43.04
8	8.36	9.1	7.68	9.72	8.41
9	142.8	68.5	100.96	22.8	35.65
17	408.75	341.3	104.4	67.0	31.94
7	8.61	9.42	7.68	8.27	6.23